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The ESS based neutrino Super Beam for CP Violation discovery

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Abstract

After measuring the last neutrino mixing angle θ_{13} and finding it relatively large, the observation of CP violation in the leptonic sector is now reachable with the condition to have significantly more intense neutrino beams than the existing ones. For this θ_{13} value, it came out that going to the second oscillation maximum instead of the first one, provides more sensitivity to CP violation. The European Spallation Source facility in Lund, designed to accelerate protons to 2.0 GeV at a repetition rate of 14 Hz for neutron production, could also be used to produce a copious number of neutrinos. Doubling the frequency of its proton linac opens the possibility to operate the facility simultaneously for neutron and neutrino production. An accumulator ring would be needed to shorten the pulses from 2.86 ms for neutrons to few μs in order to reduce to acceptable levels the electric current sent to the magnetic horn focusing charged mesons to acceptable levels for the neutrino production. This accumulator could also be used by the neutron facility to increase its performance. Coupled with a megaton Water Cherenkov far detector placed at the optimal distance, this facility could efficiently exploite the second oscillation maximum to cover a large fraction of the CP violation parameter δ_{CP} at 5 σ confidence level.

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Keywords: neutrino, Super Beam, Water Cherenkov detector, leptonic CP violation, ESS, ESSnuSB

1. Introduction

After measuring the last neutrino mixing angle θ_{13} by mainly reactor experiments [1, 2, 3], the already designed future neutrino facilities optimized to be sensitive to as low as possible θ_{13} values, had to readjust their parameters to better take into account this last measured value. All proposed new facilities supposed to provide significantly more intense neutrino beams were designed to exploite the first oscillation maximum. However, for large θ_{13} values it has been shown [4] that experiments operating at the second oscillation maximum are less sensitive to systematic errors and have better sensitivity to the CP violation parameter δ_{CP}. This comes mainly from the fact that the term in the oscillation probability carrying δ_{CP} dominates the "atmospheric" and "solar" terms at low θ_{13} values at the first oscillation maximum, while for large values this is only true when going to the second oscillation maximum. On top of that, it can be shown [5] that the neutrino/anti–neutrino asymmetry in the vacuum is approximately equal to $0.30 \sin\delta_{CP}$ at the first oscillation

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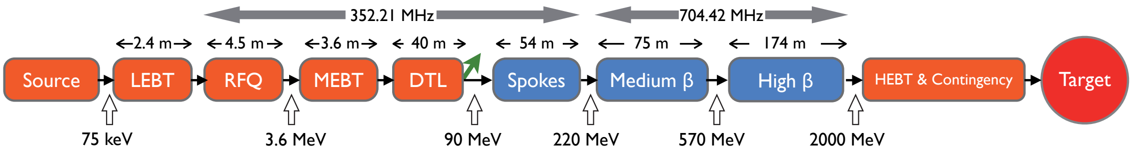

Fig. 1. Schematic view of the ESS proton linac.

maximum while for the second oscillation maximum this value becomes $0.75 \sin \delta_{CP}$. This clearly shows that experiments at the second oscillation maximum have significantly higher sensitivity to δ_{CP} than those placed at the first oscillation maximum.

In order to go to the second oscillation maximum compared to experiments operated at the first one, either the experiment baseline is increased or lower neutrino energy is used or both. A decrease of statistics is expected by increasing the baseline because of the solid angle. On top of that, if the neutrino energy goes below $\sim$ 1 GeV the neutrino interaction cross–sections decrease considerably and rapidly. For these reasons, to exploite the second oscillation maximum capabilities very intense neutrino beams are needed. Such a neutrino beam could be obtained using the European Spallation Source (ESS) [6] proton linac, under pre–construction phase at Lund, Sweden. This linac is supposed to start delivering protons at full power (5 MW) and energy (2 GeV) for neutron production in 2023.

As a starting point for these studies, the FP7 Design Study EUROν [7, 8] on Super Beams has been considered. The EUROν study was based on the CERN Superconducting Proton Linac (SPL, 4.5 GeV protons, 4 MW) [9] Super Beam and the MEMPHYS [10, 11] large Water Cherenkov detector placed in the Fréjus tunnel located at the first neutrino oscillation maximum (130 km).

Preliminary physics performance studies for the ESS neutrino Super Beam can be found in [12].

2. The ESS Proton Linac

The ESS will be a major international user facility providing slow neutrons for research laboratories and industry. The facility will be running at 14 Hz and the proton linac (Fig. 1) will deliver a proton current of 62.5 mA. The proton pulses will have a duration of 2.86 ms. The annual operation period will be 5000 hours (208 days, 1.8×10^7 sec). In table 1 the main ESS parameters are given. An empty space at the end of the linac could allow, during future upgrades, to increase the proton energy up to 3.6 GeV.

Table 1. Main ESS facility parameters concerning the proton beam.

Parameter	Value
Average beam power	5 MW
Proton kinetic energy	2.0 GeV
Average macro–pulse current	62.5 mA
Macro–pulse length	2.86 ms
Pulse repetition rate	14 Hz
Maximum accelerating cavity surface field	45 MV/m
Maximum linac length (excluding contingency and upgrade space)	352.5 m
Annual operating period	5000 h
Reliability	95%

To be able to use the linac simultaneously for neutron and neutrino users the linac frequency has to double. In this way, 5 MW mean power pulses would be send alternatively to the two users running both at 14 Hz.

The present beam pulse duration of 2.86 ms is too long for the neutrino facility. Indeed, in the present design the hadronic collector (horn) used to focus charged mesons (mainly pions) in the right direction uses a magnetic field produced by a high pulsed current (350 kA) pulsed at the frequency of 14 Hz. The duration of these pulses must not exceed few μs in order to allow an efficient cooling of the horn heated by radiations and joule effect. Also, the pulse generator must have enough time to recuperate a fraction of the already injected energy and be ready for the next pulse. Short pulses are also better for cosmic background rejection at the level of the neutrino detectors, near and far.

To reduce the proton pulses to few μs it is proposed to use an accumulation ring having a circumference of about 400 m, able to fit in the already allocated ESS area. In order to be able to inject in the accumulator ring protons while other protons are already circulating in, the ESS linac must be able to also accelerate H^- ions to avoid severe repulsion problems. An H^- source has to be added at the beginning of the linac as it is already done at SNS [13].

3. Accumulator

A 400 m diameter accumulator would shorten the proton pulses to about 1.5 μs that is very suited to the horn operation and for neutron users. Each pulse from the ESS linac will contain 1.1×1.0^{15} protons. This will lead to severe space–charge problems. A way to reduce this effect is to use 4 superimposed rings located in the same tunnel, each ring receiving 1/4 of the bunches during a multi–turn injection. Enough space between the bunches in the bunch train from the linac must be created to permit the beam distribution system to inject from one ring to the next one. Experience already exists from the CERN PS Booster [14] of using 4 superimposed rings.

The H^- ions from the linac will be stripped during the injection into the accumulator using a laser–stripping device. Due to the very high beam power, a foil stripping will probably be impossible to use because the foil would not resist. The possibility to make laser–stripping experimental tests using existing set–ups in the USA will be investigated [15].

A beam transport and distribution system already designed by EUROν can be used to distribute the proton beam to the 4 rings. The rings could be emptied one after the other during the time between two linac pulses. Precise timing operation scenarios are under investigation.

4. Target/Horn Station

A very important element of each neutrino beam is the target station. The target station (Fig. 2) includes the target itself, the hadronic collector (magnetic horn), the decay tunnel (25 m), the beam dump, shielding and servicing rooms. The design adopted here is the one already studied by EUROν, thanks to the proton energy and power similarities.

Classical monolithic solid targets are almost impossible to use for this application because of the difficulty to provide efficient cooling. As in EUROν, a packed bed of titanium spheres (few mm diameter) cooled with cold helium gas is planed to be used by this Super Beam. Tests of this configuration will be done using the HiRadMat [16] high intensity proton irradiation facility at CERN.

In order to mitigate the high proton power effects, four targets and horns are introduced in the design, sharing the full power. This EUROν choice matches well the choice of the four accumulator rings, each ring sending its beam to each target/horn system. All studies done in EUROν concerning radiations, shielding and beam dump can be found in [8].

Another critical element is the horn power supply which has to deliver at high frequency (14 Hz) about 350 kA. A design of this power supply able to go up to a repetition rate of 50 Hz can be found in [17]. In order to safe electricity, this pulse generator has to recuperate a large fraction of the energy injected in the system and use it again for the next pulse. A common generator for all four horns can be used by switching from one horn to the other.

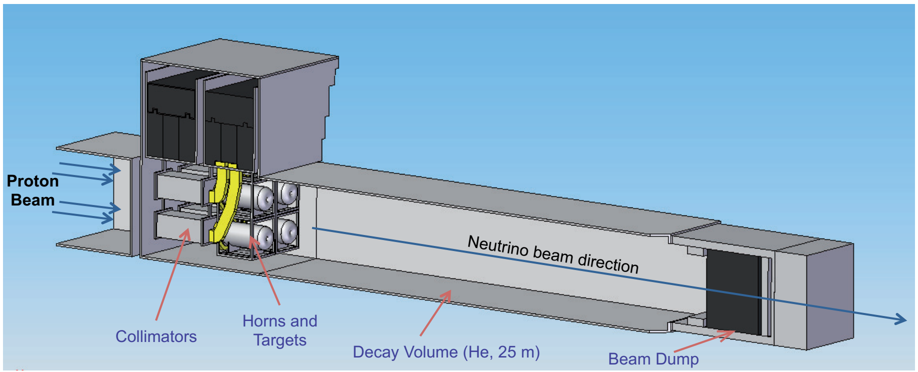

Fig. 2. Schematic view of the target/horn station.

5. Neutrino Beam Characteristics

Using the ESS proton beam and the target station described above, the neutrino and anti–neutrino energy distributions of Fig. 2 can be obtained at a distance of 100 km from the target using 2 GeV protons. Neutrinos or anti–neutrinos are obtained by focussing π^+ or π^- respectively according to the direction of the electric current in the horn. The mean muon neutrino energy is about 300 MeV. The annual operation period will be 5000 hours (208 days, 1.8×10^7 sec).

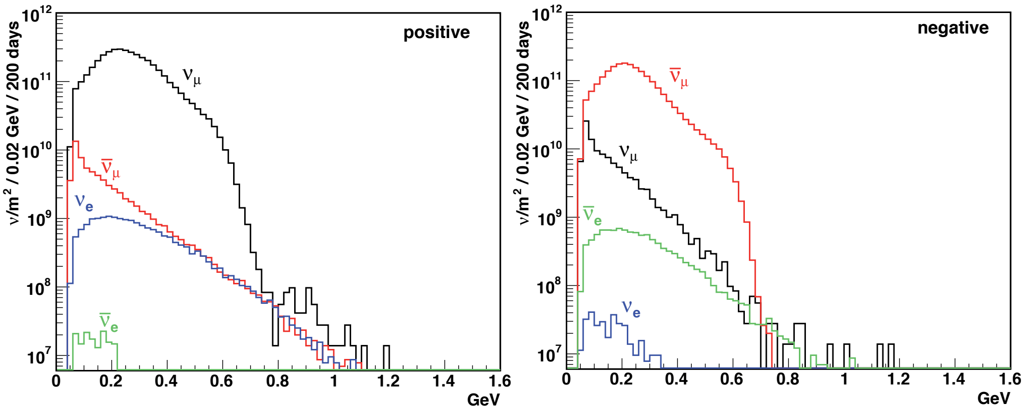

Fig. 3. Neutrino energy distribution at a distance of 100 km on–axis from the target station, for 2.0 GeV protons and positive (left, neutrinos) and negative (right, anti–neutrinos) horn current polarities, respectively.

Table 2 gives the composition of the neutrino beam for one year running. For the same running time, about 2 times less anti–neutrinos (negative horn polarity) are expected. For this reason it is proposed to run the facility for 2 years with neutrinos and 8 years with aniti–neutrinos. It is also expected to have 0.5% ν_e ($\bar{\nu}_e$) in the neutrino (anti–neutrino) beam for positive (negative) horn polarity. On one hand, this constitutes a (low) background to the $\nu_\mu \rightarrow \nu_e$ oscillation. On the other hand, these ν_e's can be used to measure neutrino cross–sections in a near detector for the energy range relevant to this project. This could help to reduce the systematic errors.

6. Underground Detector and Location

As already mentioned, the far detector will be a megaton Water Cherenkov similar to MEMPHYS. Its fiducial volume is of the order of 500 kt. Two candidate mines in Sweden located at 360 km (Zinkgruvan)

Table 2. Number of neutrinos per m^2 crossing a surface placed on–axis at a distance of 100 km from the target station during 200 days for 2.0 GeV protons and positive and negative horn current polarities.

	positive		negative	
	N_ν ($\times 10^{10}$)/m^2	%	N_ν ($\times 10^{10}$)/m^2	%
ν_μ	396	97.9	11	1.6
$\bar{\nu}_\mu$	6.6	1.6	206	94.5
ν_e	1.9	0.5	0.04	0.01
$\bar{\nu}_e$	0.02	0.005	1.1	0.5

and 540 km (Garpenberg) could host this detector. The optimal distance depends on the final ESS proton linac energy. The starting energy will be 2 GeV, while empty space in the linac allows to go during upgrades up to 3.6 GeV. As it is shown below, higher energies induce to place the far detector at longer distances.

This facility can also be used for mass hierarchy determination. In case of conflict between CP violation discovery potential and mass hierarchy determination, the former will be favoured. It is probable that mass hierarchy problem will be resolved before the next Super Beam projects start running.

Contact is already established with both mines management in order to have access to geological studies needed to determine the degree of suitability of each mine.

7. Physics Performance

In order to evaluate the physics performance GLoBES [18] has been used. A first evaluation of the CP violation and mass hierarchy determination performance can be found in [12].

To find the best baseline to place the far detector, several distances between the neutrino source and the far detector and several proton energies have been considered. For these comparisons the accuracy on δ_{CP} and the significance to reject the absence of CP violation (i.e., $\delta_{CP} = 0°,\ 180°$) have been considered.

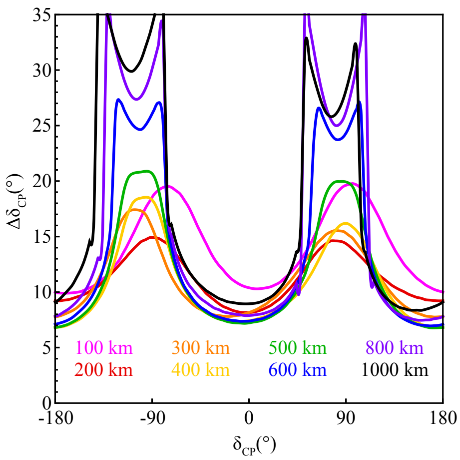

Fig. 4. δ_{CP} accuracy versus δ_{CP} for several baselines, for 2 GeV protons.

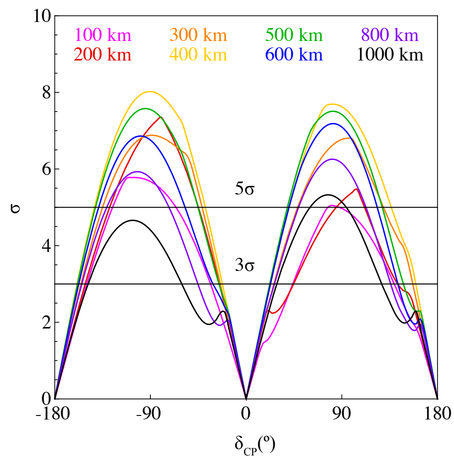

Fig. 5. The significance with which CP violation can be discovered as function of the fraction of the full δ_{CP} range for different baselines and for 2 GeV protons.

Fig. 4 presents the precision which can be achieved on δ_{CP} as a function of δ_{CP}. It is well seen that, for 2 GeV protons, the baseline must not exceed 600 km. The expected accuracy on δ_{CP} around 0° and 180°, the two values to exclude, is of the order of 7°. Fig. 5 shows the discovery significance versus δ_{CP}. Here too, in order to maximize the δ_{CP} range for which the significance is higher than 5 σ, the baseline must remain between 300 km and 600 km.

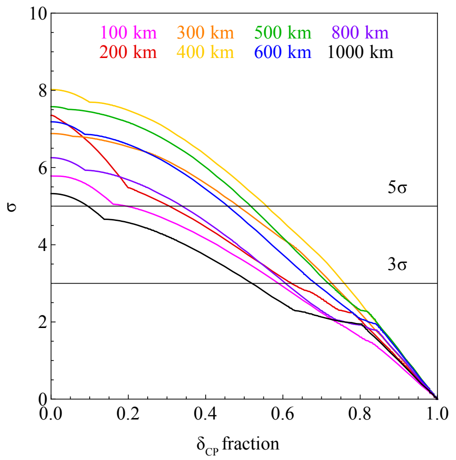

Fig. 6. The significance versus the fraction of δ_{CP} for various baselines and for 2 GeV protons.

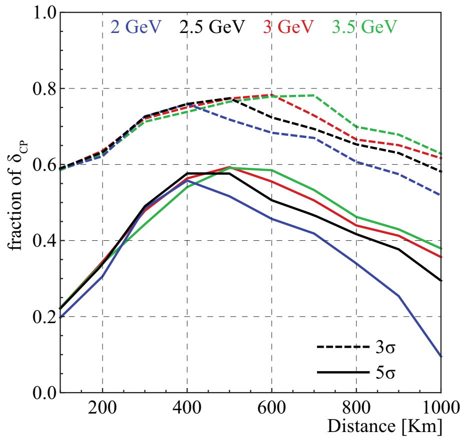

Fig. 7. The fraction of the full δ_{CP} range as function of the baseline. The lower (upper) curve is for CP violation discovery at 5 σ (3 σ) significance.

Fig. 6 presents the significance versus the δ_{CP} fraction coverage for 2 GeV protons, while Fig. 8 shows the δ_{CP} fraction coverage versus the distance for 3 σ and 5 σ discovery significance. It can be seen that 60% (78%) of δ_{CP} values could be covered at a distance around 500 km and a proton energy of ∼3 GeV, for 5 σ (3 σ) confidence level.

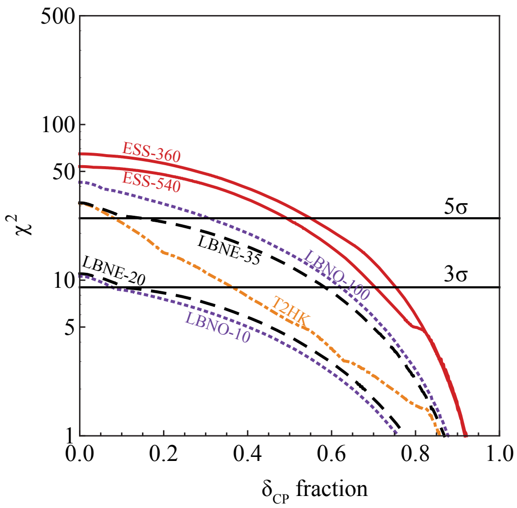

Fig. 8. The significance in terms of χ^2 with which CP violation can be discovered as function of the fraction of the full δ_{CP} range for different proposed Super Beam experiments (unknown mass hierarchy).

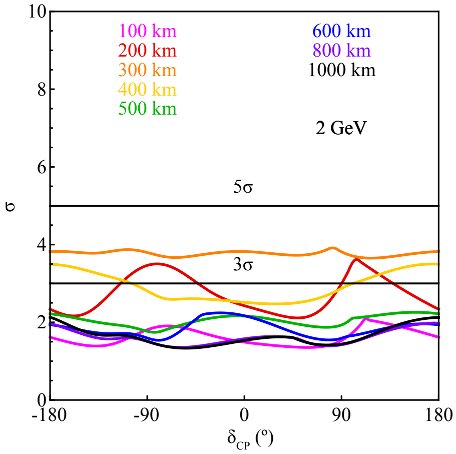

Fig. 9. The significance versus the fraction of the full δ_{CP} range for mass hierarchy discovery, for 2 GeV protons and various baselines.

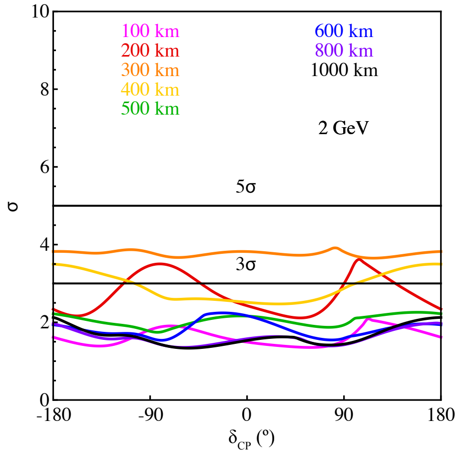

Fig. 10. The significance versus the fraction of the full δ_{CP} range for mass hierarchy discovery, for 2 GeV protons and various baselines.

The parameter values used in the GLoBES calculations are: $\Delta m^2_{21} = 7.5\times10^{-5}$ eV^2, $\Delta m^2_{31} = 2.5\times10^{-3}$ eV^2, $\theta_{21} = 0.59$, $\theta_{13} = 0.16$ and $\theta_{23} = \pi/4$. The neutrino mass hierarchy is not assumed to be known (normal hierarchy has been used for all calculations). These parameters are included in the fit assuming a prior knowledge with an accuracy of 3% for θ_{12}, 8% for θ_{23}, 3% for Δm^2_{31} and 3% for Δm^2_{12} at 1 σ level. The error in θ_{13} has been set to 5% (final uncertainty expected from reactor experiments). A systematic uncertainty of 5% was assumed for the neutrino flux normalization and a 10% systematic uncertainty for the background. Studies with higher systematic errors can be found in [19]. The data collection period assumed is two years of neutrino running plus eight years of antineutrino running in order to detect in the far detector about the same total number of events for the two kinds of neutrinos.

Fig. 8 presents a comparison of the discovery performance of several well–known proposed long baseline experiments. For ESS neutrino beam two options are presented, one for a baseline of 360 km and one for 540 km, both assuming 2 GeV proton beam kinetic energy. For a baseline of 360 km, 55% (75%) of the δ_{CP} fraction can be covered at 5 σ (3 σ) confidence level, while for 540 km this fraction is reduced to 50% (70%). For low proton energy (< 3 GeV), 360 km baseline becomes more performant than 540 km. For all projects it has been assumed 5% systematic error on signal and 10% for background.

Even if the baseline is not very large, this project has also a significant sensitivity to the neutrino mass hierarchy. Fig. 9 and 10 present the significance to discover the neutrino mass hierarchy versus δ_{CP}. In order to have a 5 σ discovery the proton energy must be at least 3 GeV. To improve the mass hierarchy performance atmospheric neutrinos can be used [20]. Indeed, the copious number of atmospheric neutrinos which could be detected by the gigantic far WC detector combined with those produced by the neutrino Super Beam could help to overpass the 5 σ discovery limit even for 2 GeV protons.

8. Conclusion

The European Spallation Source linac will start delivering protons for neutron production at full energy and power in 2023. A neutrino Super Beam based on this 2 GeV proton linac has the potential to become, during the next decade, the most intense neutrino beam in the world. This facility can be efficiently used for CP violation discovery in the leptonic sector fully exploiting the advantages of the second oscillation maximum.

The present studies are based on simulations of $\nu_\mu \to \nu_e$ oscillation of an initially almost pure ν_μ beam produced with the use of the ESS proton linac and of the detection of ν_e using a very large Water Cherenkov

MEMPHYS–like detector . The preferred range of distances from the neutrino source to the detector site, for CP violation discovery, is found to be between 300 km and 550 km.

With eight years of data taking with an anti–neutrino beam and two years with a neutrino beam, up to 60% of the total CP violation δ_{CP} phase range could be covered at 5 σ level at the optimal baseline of around 500 km. There are two particular underground mines with baselines of 360 km and 600 km, and with a depth of more than 1000 m, which could be used to host the underground neutrino far detector. Geological studies for these two mines are under way.

Further optimizations of the target station parameters and also of the detector design, are planned to improve the sensitivity of the measurement of an eventual leptonic CP violation.

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